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Frontiers in Fine-Scale *in situ* Studies: Opportunities During the SWOT Fast Sampling Phase

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Conceived as a major new tool for climate studies, the Surface Water and Ocean Topography (SWOT) satellite mission will launch in late 2021 and will retrieve the dynamics of the oceans upper layer at an unprecedented resolution of a few kilometers. During the calibration and validation (CalVal) phase in 2022, the satellite will be in a 1-day-repeat fast sampling orbit with enhanced temporal resolution, sacrificing the spatial coverage. This is an ideal opportunity – unique for many years to come – to coordinate *in situ* experiments during the same period for a focused study of fine scale dynamics and their broader roles in the Earth system. Key questions to be addressed include the role of fine scales on the ocean energy budget, the connection between their surface and internal dynamics, their impact on plankton diversity, and their biophysical dynamics at the ice margin.

Keywords: remote sensing, ocean dynamics, energy cascade, biogeochemical processes, submesoscale, mesoscale

INTRODUCTION

Importance of Fine Scales

The oceanic fine scales (1–100 km) have relatively short time scales but crucially affect ocean physics and ecology up to the climate scale, due to the strong gradients created by energetic dynamics (Ferrari and Wunsch, 2009; Su et al., 2018). These gradients are associated with strong vertical transport, connecting the ocean's upper layer to its interior (Lévy et al., 2001; Ferrari, 2011). The horizontal and vertical fine-scale dynamics modulate the energy cascade (McWilliams, 2016) as well as ice-sea (Manucharyan and Thompson, 2017)

and air-sea (Lehahn et al., 2014; Sasaki et al., 2014; Renault et al., 2018) interactions. The temporal scale associated with these horizontal and vertical fine scales is days to weeks, the same as in many important ecological processes including phytoplankton demography and competition, and the duration of foraging trips for many marine predators. This temporal resonance is one of the reasons behind the fine-scale variability that appears in marine ecosystems and their services, including biogeochemical cycles (Lévy et al., 2012; Olita et al., 2013; McGillicuddy, 2014; d'Ovidio et al., 2015; Mahadevan, 2016; Lehahn et al., 2018), biodiversity (d'Ovidio et al., 2010; Lévy et al., 2015), fish distribution (Godø et al., 2012; Watson et al., 2018), and even foraging strategies of megafauna (Tew Kai et al., 2009; Della Penna et al., 2017).

A Troubling Gap at the Global Scale Between Fine-Scale Modeling and Observing Capacities

On the modeling side, great progress has been made in characterizing this regime over the past few decades. Physical and biophysical configurations for processes of the order of 10 s of km are now considered standard for regional circulation models. Field campaigns like AlborEx (Pascual et al., 2017), LatMix (Shcherbina et al., 2015), LATEX (Petrenko et al., 2017) have also shown that individual fine-scale features may be experimentally targeted. The frontier now stands in the integrated role of the fine scales in the Earth system: what are their net global impacts? How do their properties vary regionally and seasonally? On this topic a troubling gap has formed between models and observations. Field campaigns can target individual features, but they represent a tiny fraction of the possible ocean conditions. Moreover, most *in situ* studies are biased by the choice of stronger and longer-lived fine scales, which are the only ones that can be reliably tracked today with remote sensing tools. We rely on models extending these observations to the global ocean (e.g., Qiu et al., 2018), but this knowledge gap between models and observations at the global scale may hide key physical or biophysical mechanisms that models do not represent correctly.

The Role of Remote Sensing and the SWOT Mission

In order to address this knowledge gap, the scientific community has been focusing on novel platforms. Among these are satellite missions that will provide global coverage at high spatiotemporal resolutions. Remote sensing does not provide ground truth of all fine-scale physical and biophysical processes, but can provide a critical synoptic context for fine-scale features, helping to separate spatial from temporal variability, supporting strategies for *in situ* field campaigns, and assessing the representativeness of *in situ* data. A future fine-scale resolving satellite mission is the NASA/CNES SWOT (Surface Water and Ocean Topography) satellite mission, to be launched at the end of 2021 (see details in the Morrow et al., 2019 SWOT paper in this same issue). SWOT is an altimetric mission. While satellite altimetry today provides one-dimensional, along-track observations, SWOT will provide wide-swath, two-dimensional sea surface height (SSH) fields similar to sea surface temperature (SST) and ocean color

fields, but without being affected by clouds, due to its microwave Ka-band radar interferometer. SWOT will directly provide a key dynamic variable of the ocean, SSH, with a 2D view at an unprecedented resolution (15–30 km in wavelength, depending on sea state: see Morrow et al., 2019 for details).

Two Phases, One Unprecedented Opportunity

The SWOT mission is characterized by two temporal phases. The first phase is for mission calibration and validation. It will last 3 months (January–March 2022) with a 1-day-repeat cycle (so-called “fast-sampling phase”). The second phase (so-called “nominal orbit”) will have a 21-day-repeat cycle and last several years (Morrow et al., unpublished). Here we focus on the unprecedented experimental opportunities offered by the fast-sampling phase in early 2022. These cloud-free SSH observations are available across large regions (120 km wide swaths and their crossing point, so-called “crossovers,” see **Figure 1**). These are distributed all around the globe, with a temporal resolution of 1 day. This 1-day repeat has never been available with the conventional nadir-looking altimetry in the past and is not expected from other planned missions in the future. In the following we present some of the observational opportunities for which SWOT is expected to be especially useful, as well as challenges and recommended practices for interpreting its maps. Examples of *in situ* campaigns that are planned under SWOT crossovers are then described.

SCIENCE OPPORTUNITIES FOR PHYSICAL AND BIOPHYSICAL PROCESSES

Studying the energy budget in the ocean requires fine-scale observations. The dynamics of fine scales plays a key role in both the direct and inverse energy cascade (McWilliams, 2016) and therefore in the regulation of the ocean energy budget. Fine scales are associated with potential energy to kinetic energy conversion in high wavenumbers (Boccaletti et al., 2007) and eventually kinetic energy dissipation (Nikurashin et al., 2012). A precise spatial and temporal representation of these processes is required for a correct estimation of the ocean energy budget and for designing optimal parameterizations for high resolution, as well as climate resolving numerical models. For example, the intensity of the fine-scale density gradients and vertical velocities in numerical models strongly depends on the rate of kinetic energy accumulation along the direct cascade, before being dissipated by microscale non-linear processes.

Today, there are no direct fine-scale observations of ocean currents from space. Surface geostrophic currents derived from satellite altimetry maps only represent large scales > 150–200 km (Chelton et al., 2011) which are mostly in quasi-geostrophic balance. At spatial scales smaller than 200 km, geostrophic or cyclo-geostrophic motions are not always dominant. SWOT SSH will observe both balanced (eddies) and unbalanced (internal tides and internal gravity waves) motions at these scales. This is

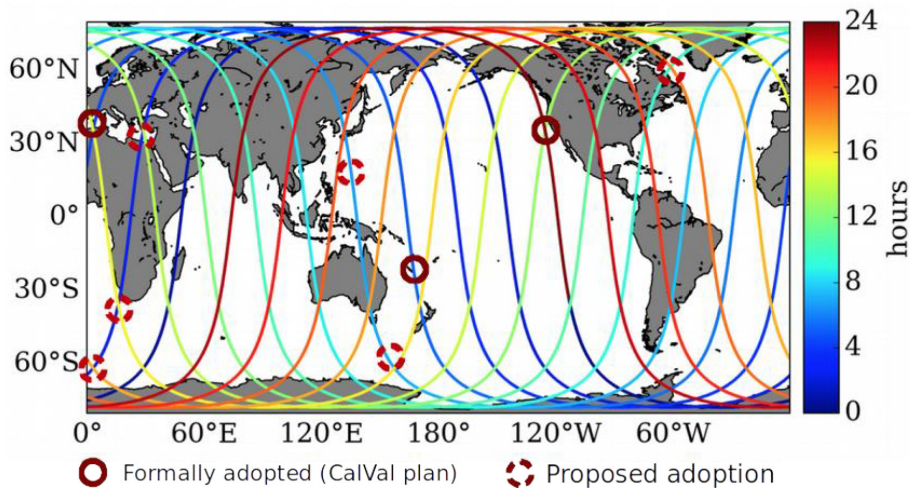


FIGURE 1 | SWOT orbit during the fast-sampling phase [adapted from Wang et al., 2018, ©Copyright (2017) AMS]. During the first months of the mission (expected for January–March 2022), the satellite will be on a special orbit which will overfly a smaller portion of the global ocean with a repeat cycle of 1 day (twice per day on crossovers). This so-called fast-sampling phase will resolve both the spatial and the temporal variability of the ocean fine-scale features along the ~120 km wide swath. Successively, the nominal orbit of SWOT will cover the entire globe (between 78 N and 78 S) with a repeat cycle of 21 days. The circles represent the study regions discussed in Section “Some Case Studies for the SWOT Fast-Sampling Phase.”

an opportunity to characterize their 2D spatial structure globally, and to observe their interactions, important for the ocean energy budget, mixing and dissipation.

Biophysical couplings at fine scales present large uncertainties, introducing a notorious main source of error in representing ocean dynamics on a variety of interdisciplinary issues, ranging from the biological carbon pump and its associated export (Lévy et al., 2012; Siegel et al., 2016) to plankton diversity and spatial planning of commercial fisheries (Scales et al., 2018; Watson et al., 2018) and marine protected areas (Della Penna et al., 2017). The observations during the SWOT fast-sampling phase present a novel opportunity for studying the ecology of microbial populations, in particular when paired with high throughput techniques. Characterization of the microbial community structure by morphological techniques [automated flow cytometry Marrec et al. (2018)] and machine learning applied to microscopy as well as “-omics” techniques (e.g., Villar et al., 2015) are underway and now provide the possibility of repeatedly mapping the fine-scale planktonic community structure and dynamics on regions spanning several tens of km in a quasi-synoptic way. When deployed on the regions overflown by SWOT during the fast-sampling phase, these techniques should yield empirical evidence of the ecological effect of impulsive events tied to fine-scale physics (Talmy et al., 2014).

Finally, SWOT data during both the fast-sampling and nominal phases have a high potential for marine ecology applications. Animal telemetry studies have shown to greatly benefit from the comparison with altimetry-derived circulation features (e.g., Della Penna et al., 2017). These biologging data are the cornerstone for the spatial planning of marine protected areas. However, biologging fine-scale resolving precision, which is now routinely available, remains largely unexploited due to resolution limitations in nadir altimetry gridded products.

CHALLENGES FOR COMBINING SWOT AND IN SITU OBSERVATIONS

Entanglement of Space and Time Variability

In most cases, a detailed understanding of the fine-scale processes associated with SSH fine-scale physical features will not be possible on the basis of satellite information alone but will require *in situ* information as well. In this regard, a fine-scale *in situ* observing network optimized for SWOT observations should ideally instrument a region ~100 km × 100 km wide, with a ~km horizontal spatial resolution and ideally hydrographic profiles extended up to the bottom. The key challenge, however, is the time constraint. The daily or shorter temporal resolution required to disentangle fine-scale spatial and temporal variability, currently renders a regular mapping which respects all these requirements out of the reach. The definition of a fine-scale sampling strategy is therefore a critical task which consists of choosing which aspects to favor and which to sacrifice (Wang et al., 2019). Viable solutions (Shcherbina et al., 2015; Jaffe et al., 2017; Pascual et al., 2017; Petrenko et al., 2017; Wang et al., 2018; see also section “Some Case Studies for the SWOT Fast-Sampling Phase”) include the use of an affordable number of moorings deployed on a smaller area, or along a one-dimensional array; the restriction to ship-based shallow CTD casts and to instruments in use, to minimize the occupation time at sample stations; the coordinated use of autonomous platforms; and the use of non-regular, time-dependent (i.e., adaptive) grids. All these strategies may benefit from near-real time feature detection (e.g., d’Ovidio et al., 2015) from satellite and *in situ* data, in order to optimize the position and orientation of the sampling grid.

Entanglement of the Balanced and Unbalanced Motion

At spatial scales <200 km, the combined observation of balanced (eddies) and unbalanced motions (internal gravity waves and internal tides) impose great challenges in interpreting and fully utilizing the high-resolution SWOT SSH data (Qiu et al., 2018). In contrast to the majority of the larger SSH features observed with nadir altimetry, not all the SSH fine-scale gradients correspond to quasi-geostrophic currents. Recommended approaches for disentangling the two components exist and need to be implemented in order to avoid errors in the interpretation of SWOT observations. First of all, the regional and seasonal variation should be considered, as the relative strength of balanced and unbalanced motion greatly varies in space and time (Torres et al., 2018). The transition scale from balanced to unbalanced motion, as well the seasonal variations of their relative strength have been documented with good accuracy from both model studies and *in situ* observations (Qiu et al., 2017). These data can provide valuable *a priori* information to disentangle balanced and unbalanced motion. Internal tides contribute a significant SSH signature at scales <200 km, and coherent internal tide corrections are being developed to remove tides from future fine-scale altimetry and *in situ* data (e.g., Zaron and Ray, 2017). In addition, *in situ* ADCP or glider measurements will also help the eddy-wave separation following the framework provided in Rainville et al. (2013).

SOME CASE STUDIES FOR THE SWOT FAST-SAMPLING PHASE

The primary objective of the fast-sampling phase is mission CalVal. During this period, orbit crossovers will open opportunities for challenging *in situ* data with several processes, which until now, mainly addressed model studies (like the ones described in section “Science Opportunities for Physical and Biophysical Processes”) on a variety of ocean regions. These opportunities are unique in providing synoptic images of the fine-scale ocean circulation twice a day. The SWOT nominal period for the fast-sampling phase is January–March 2022. With an acknowledgment of the risk of the mission being postponed due to unplanned technical delays, the SWOT Science Team encourages the international community to coordinate future fine-scale campaigns around the world so that a large number of SWOT crossovers will be occupied by *in situ* studies during the fast-sampling phase. Besides the principal CalVal site in the California Current System (Wang et al., 2018; Morrow et al., unpublished), we present here some other possible locations (Figure 1) and the associated planned *in situ* activities at various levels of maturity.

The Western Pacific: Energetic Mid-Latitude Sites and Tropical Regions With Internal Tides

The Subtropical Countercurrents in the Western Pacific is baroclinically unstable, producing energetic eddies. In this

region, the Pilot National Laboratory for Marine Science and Technology (Qingdao) is planning an *in situ* observing system along the SWOT ground track as part of its Ocean Energy Cascading Observation Study, aiming to validate and complement the SWOT measurements. Three moorings will be deployed in a triangular shape separated by ~20 km. They will collect hydrographic records over the upper 3000 m to calculate dynamic height and infer SSH and velocity records above the main thermocline (~500 m). With sufficient funding support, this mooring system could be extended over a larger spatial domain by deploying additional moorings or gliders as substitutes. The collected data should provide a benchmark for validating the SWOT-measured SSH and the inversion of three-dimensional ocean flows based on SSH. Within the triangular mooring system, additional underwater and wave gliders are planned to resolve processes toward the submesoscale (~3 km).

In the region around New Caledonia in the South-West Tropical Pacific, where strong internal tides are observed, another study is planned in the framework of the SWOT CalVal plan. Deployments of moorings, gliders, and ship-borne studies using underway CTDs and AD will be used to understand and characterize the interactions between high frequency motions and mesoscale activity.

Polar and Subpolar Regions The Antarctic Circumpolar Current

The Southern Ocean is a major player in the heat (Liu et al., 2018) and carbon (DeVries et al., 2017) uptake and transport, with the Antarctic Circumpolar Current (ACC) being the strongest current in the world, with hotspots occurring where the current interacts with topographic features (e.g., Chapman and Morrow, 2014). In recent years, studies have pointed to fine-scale processes that are able to dominate biogeochemical transfers (e.g., Swart et al., 2015). During the 1-day repeat phase, one SWOT track will cross the ACC upstream from Macquarie Ridge, a highly energetic ocean environment. This region has a high signal-to-noise ratio in SWOT measurements compared to adjacent ACC areas (Wang et al., 2019). It is of great interest, with expected sub-mesoscale signals in the form of internal waves, sub-mesoscale eddies and other potential small-scale features while crossing some sharp fronts of the ACC. The daily-repeat SWOT measurement allows the detection of the coherence of features and their connection to *in situ* observations (ship-based, floats, moorings, drifters, gliders). A pre-SWOT cruise (October 2018) in the area led by IMAS/CSIRO/ACE-CRC will be the base prototype of an *in situ* effort to be proposed in 2022 during the SWOT fast sampling phase.

Another Southern Ocean crossover is located in the Cape Basin. Interactions between the Agulhas Current Retroflexion, its associated shedding of large (order of 200 km) Agulhas Rings, circulation of the Benguela Upwelling Region/ Benguela Drift, and the northern domains of the ACC, provide a truly complex “cauldron” of oceanic flows (Dencausse et al., 2011) that have climate-relevant impacts at both regional and global scales. Large thermohaline horizontal gradients,

strong shear flows and intense atmosphere-ocean exchanges (Rouault and Lutjeharms, 2000) are associated with these interactions and can fuel baroclinic instabilities that evolve rapidly and at a small scale. The protrusion of the edge of the Agulhas Bank and other bathymetric features (Agulhas Ridge, the Protea, Simpson, Wyandot, Schmit-Ott seamounts) allows for an energy exchange between a very active meso- to submesoscale flow field (Dencausse et al., 2011; Kersalé et al., 2018) and underlying topography, causing further instabilities and variability. SWOT information can be contextualized with past or ongoing observational efforts in the region (the eastern SAMBA tall moorings PIES and Argo vertical profiles, glider deployments, and monitoring lines, – Du Plessis et al., 2017; Krug et al., 2017; Kersalé et al., 2018). Logistically, the relative proximity of Cape Town, research ships and existing facilities, provide reasonable access to the site to conduct ship-based surveys and deployments of high-resolution sampling platforms such as profiling gliders and autonomous surface vehicles.

Sea-Ice Dynamics and Subpolar Seas

Other opportunities for both hemispheres come from the potential use of SWOT observations to study the interactions of the cryosphere (the ice shelves, the icebergs and the sea ice) with the open ocean. The structures are commonly observed from satellite images of sea ice but are not, or are poorly observed by available altimetry satellites due to orbit limitations, a coarse resolution or the proximity of coastlines – all issues that will be addressed by the SWOT mission. For example, Manucharyan and Thompson (2017) recently showed with a model study that eddies and filaments form in the Marginal Ice Zone (MIZ) at the time of sea ice melt, due to baroclinic instabilities caused by salinity and temperature gradients. These features persist for several days and induce large oceanic vertical velocities (10 m d^{-1}). In addition, fine-scale physical information ought to be linked to the recent discovery of sea ice fall in algal bloom that can directly be observed from satellites (Lieser et al., 2015). The interactions between ice shelves and the ocean are also prone to form ocean mesoscale eddies at the front of ice shelves (Li et al., 2017). These “shelf-eddies” might play an important role in the transfer of heat toward the ice shelves, and on the biogeochemistry of the coastal Southern Ocean. In the Southern Hemisphere, there are several SWOT crossovers which will fall over the Antarctic ice margin zone and over the Antarctic shelf break, which therefore are good candidates for the aforementioned problems. In the Northern Hemisphere, one of the SWOT ground tracks crosses a series of hydrographic sections located in the Labrador Sea, a biologically rich sub-arctic sea regularly monitored by Fisheries and Oceans Canada (DFO) as part of the Atlantic Zone Monitoring Program. Ship time and monitoring data could be leveraged to perform a dedicated experiment during the CalVal phase.

The Mediterranean as a Lab for Developing Fine-Scale *in situ* Strategies

Two SWOT crossovers fall within the western and eastern Mediterranean basins, respectively. One on the northern flank

of the Algerian current, between Algeria and the Balearic Island; and one in the middle of the Rhodes’ gyre. Due to its small deformation radius compared to the gaps between ground tracks at mid-latitudes, the Mediterranean sea is a region where nadir altimetry is known to capture only a small part of the mesoscale dynamics, and therefore, where SWOT is expected to provide a substantial improvement. The presence of low tides, of relatively weak internal wave dynamics (with peaks of activity mainly confined to specific and known regions), together with low cloud coverage, are further reasons for considering the Mediterranean crossovers in interdisciplinary studies.

Both sites display interesting dynamics. The western site is in a region where meanders of the Algerian current pinch off forming mesoscale eddies that propagate cyclonically from the African coast toward the Balearic abyssal plane. This Algerian current transports fresher water of Atlantic origin possibly enriched by nutrient input along the north African coast. In May 2018, the French-Spanish collaborative campaign PROTEVS-PRESWOT tested the implementation of coupling fine-scale physics with fine-scale biological measurements. The objectives of this joint experiment was to (1) evaluate the interest of the western Mediterranean SWOT crossover, (2) gain experience in multi-platform, multi-institution campaign coordination with the constraint imposed by traces of the SWOT satellite, and (3) explore the dynamics present in this region, that has been scarcely sampled in the past with only some recent high-resolution data collected by underwater gliders (Heslop et al., 2017; Aulicino et al., 2018). This work builds on several previous fine-scale experiments in the Western Mediterranean Sea (Nencioli et al., 2011; Pascual et al., 2017; Petrenko et al., 2017; Marrec et al., 2018).

CONCLUDING STATEMENT

The SWOT fast-sampling phase will provide a three-month window in early 2022, with intensive temporal sampling at the cost of spatial coverage. The opportunity to have *in situ* deployments for instrumenting under SWOT swaths during this period, particularly at crossovers, should not be missed: the comparison between *in situ* data and SWOT synoptic maps will provide an unprecedented view of the fine-scale variability in different dynamical regimes in multiple ocean basins. These data will serve as an empirical basis for interpreting future fine-scale observations over the next decade, quantifying the role of fine-scale dynamics in the Earth system.

AUTHOR CONTRIBUTIONS

Fd’O, AP, JW, AD, ZJ, SM, GG, SSw, SSp, FC, BL, and RM wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of Interest Statement: YC was employed by company Remote Sensing Solution and is also affiliated with Seatrec, Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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